
Personal Computer (PC) Based Image Processing Applied to Fluid Mechanics

Y-C Cho and B.G. McLachlan, Ames Research Center, Moffett Field, California

October 1987



National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, California 94035

ABSTRACT

A PC based image processing system was employed to determine the instantaneous velocity field of a two-dimensional unsteady flow. The flow was visualized using a suspension of seeding particles in water, and a laser sheet for illumination. With a finite time exposure, the particle motion was captured on a photograph as a pattern of streaks. The streak pattern was digitized and processed using various imaging operations, including contrast manipulation, noise cleaning, filtering, statistical differencing, thresholding, etc. Information concerning the velocity was extracted from the enhanced image by measuring the length and orientation of the individual streaks. The fluid velocities deduced from the randomly distributed particle streaks were interpolated to obtain velocities at uniform grid points. For the interpolation we used a simple convolution technique with an adaptive Gaussian window. The results are compared with a numerical prediction by a Navier-Stokes computation.

1. INTRODUCTION

An important task in experimental fluid dynamics is determination of flow velocities. Most of the commonly used methods, such as hot wire anemometry and laser Doppler velocimetry, measure flow velocity at one spatial location at a time.¹ With repeated measurements at extended spatial locations these methods can be used to determine the velocity field of a steady flow or the phase-locked average velocity field of a periodic unsteady flow. A more challenging undertaking is measurement of the velocity field of a non-periodic unsteady flow. Conventional point-measurement methods, such as those mentioned above, are not suitable for such measurements. Thus fluid dynamicists have been seeking new methods that exploit modern computer technology. These new methods include laser speckle velocimetry (LSV) and particle image velocimetry (PIV), which are still in the process of being developed.²⁻⁴

We recently embarked on a research program to develop image processing techniques applied to the measurement of the velocity field of unsteady flow. For the initial phase of the program, PC based image processing was used to determine the velocity field around a circular cylinder which was subjected to an impulsive linear motion. The "Particle Streak Method" was employed for measurement. The concept is simple and dates back to the early part of the century.^{5,6} Despite its long history and inherent simplicity, this method was not previously viable largely because the manual manipulation of the images required too much time and effort. Advancement in digital image processing technologies has recently revived interest in the method.^{7,8} In its applications, sometimes excessive emphasis has been placed on automation of data reduction, and a good portion of the significant image data is discarded to avoid the risk of including wrong data. To accumulate sufficient data points to map out the velocity field, repeated image detection of a specific state is required. Such repetition is in practice feasible only for steady flow. In the present study, we use a semi-automatic data-reduction scheme, which can recover significant image data much more efficiently than a currently available automatic scheme.⁹

In the proceeding sections, we will describe the image processing system, the experimental setup for taking streak images, the enhancement of the images, extraction of the binary images, determination of the velocities from the binary images, and interpolation of the velocities. It will be followed by discussions of the results, which are compared with a numerical prediction made by a Navier-Stokes computation.

2. IMAGE PROCESSING SYSTEM

A schematic diagram of the image processing system is shown in Fig. 1. The host computer is an IBM PC AT with 1 MB memory and a 40 MB hard disk. A real-time image processor (Imaging Technology Inc.'s FG 100-512-3-60 AT) is installed in the PC. The image is acquired from a video camera or a video tape. The image, digitized and stored in the memory, is displayed on the RGB monitor. An on-line printer is connected to the PC. The main image processing software includes ImageLab and ImageTool, developed by Werner Frei Associates.

The system is interfaced with the NASA Ames Computer Network via Ethernet. This interface alleviates the limit of the computation capability of the PC based system. Image processing algorithms which may require

ORIGINAL PAGE IS OF POOR QUALITY

large memory and sophisticated subroutines can be executed on the NASA Ames computers such as MicroVax, Vax, or Cray.

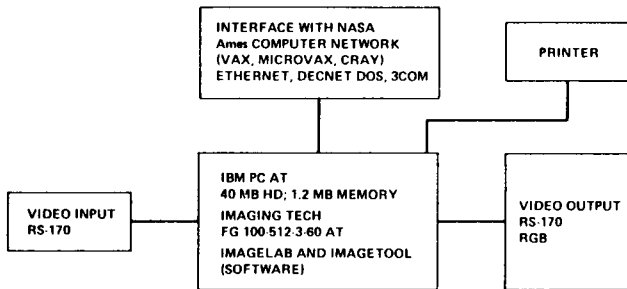


Figure 1. Schematic diagram of PC based image processing system.

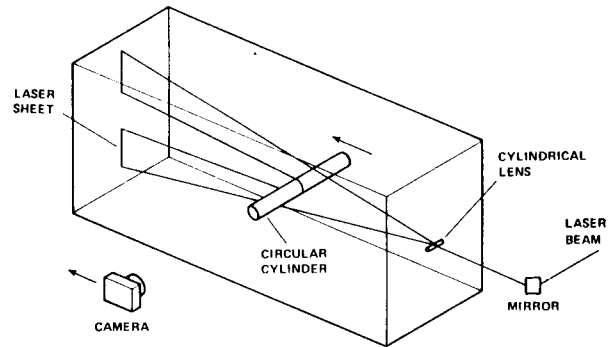


Figure 2. Experimental arrangement used to obtain streak photograph.

3. EXPERIMENTAL SETUP

A schematic of the experimental arrangement is shown in Fig. 2. Shown is a water towing tank that has glass walls for viewing and an open top. The tank is 48 in. in length, 20 in. in height, and 13 in. in width. The circular cylinder model is of 0.5 in. diameter and 11 in. span, and was horizontally fixed between two Plexiglas endplates that are attached to a lead-screw assembly atop the tow tank. At time $t = 0$ the cylinder was impulsively set into motion with a constant speed in a horizontal direction normal to its span.

The flow was visualized by means of a suspension of neutrally buoyant seeding particles in water illuminated by a laser sheet that was vertically aligned with the tank centerline and the direction of motion. Short time exposure photographs of the induced particle motion in the plane of illumination were taken successively at regular intervals in the cylinder motion. The photographs were taken using ASA 160 color film and a 35 mm single-lens-reflex camera equipped with a 55 mm macro lens set at f2.8. The camera was moved with the model to produce the streak pattern as seen by an observer in the model frame of reference. The particles used were made of Pliolite ACL and ranged in diameter from .0021 to .0035 in.

4. PROCESSING OF STREAK IMAGE

The photographs of the time sequence may be processed and analyzed to study the time development of the flow past the cylinder. This paper, however, reports preliminary results limited to the image processing of a single photograph of streaks. Shown in Fig. 3 is the chosen photograph which was taken at the time when the cylinder had travelled the distance of six cylinder radii. The speed of the cylinder was 0.31 in./sec., the exposure time 0.5 sec, and the Reynolds number 100.



Figure 3. Photograph of particle streaks.



Figure 4. Enhanced image of streaks.

ORIGINAL PAGE IS OF POOR QUALITY

The image of the streak photograph was acquired through the video camera, and was then digitized and stored in memory and on the hard disk. The image was enhanced using various enhancement operations including contrast manipulation, statistical differencing, filtering, noise cleaning, etc. An enhanced image of the streaks is shown in Fig. 4. First, each streak is visually examined. The good streaks are then traced semi-automatically using the mouse to generate their binary image. As the optimum enhancement operations sometimes vary from one region to another, additional enhancements were applied during the tracing. In this manner, we recovered most of the significant streaks, generating the binary image of 303 streaks as shown in Fig. 5. With a typical automatic data reduction, no more than one tenth of these streaks would be salvaged.⁹

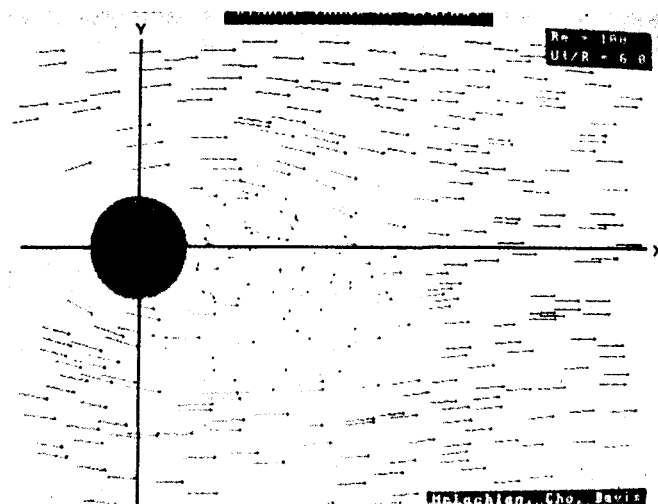


Figure 5. Binary image of streaks.

5. VELOCITY DETERMINATION AND INTERPOLATION

Each binary streak corresponds to a velocity vector. However, the streaks cannot be used immediately for determination of the velocities because of image distortion sustained in the digitization process. The distortion may be caused by the video camera, the image processor, the display element, or by combinations of these elements. To correct the distortion, we used a transformation from the image memory coordinates to another coordinate system, which we call the graphic coordinate system. To this end, we used the digitized image of a piece of regular graph paper. A finite number of uniform grid points on the graph paper were identified with the corresponding image memory coordinates. The transformation of a pixel is found by means of the bilinear interpolation of the four nearest grid points. The velocity vectors are determined in the graphic coordinate system, with the cylinder radius used as the reference length.

A binary streak can be specified in terms of the coordinates of its end pixels which are ordered properly for the direction. Let $[Xstart(i), Ystart(i)]$ and $[Xend(i), Yend(i)]$ be the graphic coordinates respectively of the first and the last pixel of the i -th streak. The velocity vector is then obtained as

$$V_x(i) = f [Xend(i) - Xstart(i)] / T, \quad (1)$$

$$V_y(i) = f [Yend(i) - Ystart(i)] / T. \quad (2)$$

Here, f is the length scale factor, the actual cylinder radius divided by the radius of the cylinder image in the graph coordinate system; T is the exposure time; $V_x(i)$ and $V_y(i)$ are respectively the x - and y -components of the velocity vector corresponding to the i -th streak.

Since the particle moves along the streak during the exposure, the coordinate of the velocity vector requires clarification. In general, the coordinate $[x(i), y(i)]$ may be obtained as

$$x(i) = [a Xstart(i) + b Xend(i)] / (a + b), \quad (3)$$

$$y(i) = [a Ystart(i) + b Yend(i)] / (a + b), \quad (4)$$

where a and b are parameters to be adjusted for the best representation.

Equations (1) and (2) determine the velocity vectors at the locations where the binary streaks are recovered. It is frequently desired to interpolate the velocities at some other locations. Here we use a simple convolution with an adaptive Gaussian window.^{7,10} The velocity vector $\vec{V}(x,y)$ at the graph coordinate (x,y) is obtained as

$$\vec{V}(x,y) = \frac{\sum_i \vec{V}(i) e^{-\{[x-x(i)]^2 + [y-y(i)]^2\}/h^2(x,y)}}{\sum_i e^{-\{[x-x(i)]^2 + [y-y(i)]^2\}/h^2(x,y)}} \quad (5)$$

where $h(x,y)$ is the width of a Gaussian window and its optimum value is inversely proportional to the square root of the density of the streaks.

This interpolation has been chosen for the following reasons: First it is simple to use, particularly for the interpolations from data points of a nonuniform distribution as in the present study. Another reason is that the seeding particles, and thus the streaks are of a random or a Gaussian distribution, and this fact is philosophically consistent with the choice of the Gaussian window formula.

6. DISCUSSIONS AND CONCLUDING REMARKS

The velocity vectors interpolated at the uniform grid points are displayed in Fig. 6. The velocity field in the wake of the cylinder is magnified in Fig. 7. In Figs. 8 and 9 the x - and y -components of the velocities are plotted as a function of y for various values of x . Also shown in Figs. 8 and 9 is a numerical prediction made by a Navier-Stokes computation. The measurement and the computation are in good agreement except in the wake and in the regions where the velocity gradient is large.

Even in the regions of the poor agreement the variation of the velocity direction agrees well. The discrepancy in the magnitude of the velocity fields between the measurement and the computation is partly attributed to the image processing errors. An error arises from the fact that the streak photograph does not contain a sufficient number of streaks in the regions where large velocity gradients occur. One may wonder if the measurement can be improved with an increase in the number of seeding particles. It is not the case. In fact, there exists a limit of the seeding particle density arising from the required inter-particle distance compared with the streak length and from the finite size of the seeding particles. We are currently developing a technique to minimize or hopefully to remove this restriction. Another error arises from the fact that the streaks are short in the vicinity of and in the wake of the cylinder.

It is obvious that the short streaks are measured with a large uncertainty compared with the long streaks. This results in relatively large errors. We believe that this deficiency can be overcome with the use of velocity biased photography. For instance, the streak photograph can be taken from a stationary camera, generating long streaks near the cylinder and short streaks in the far-field regions.

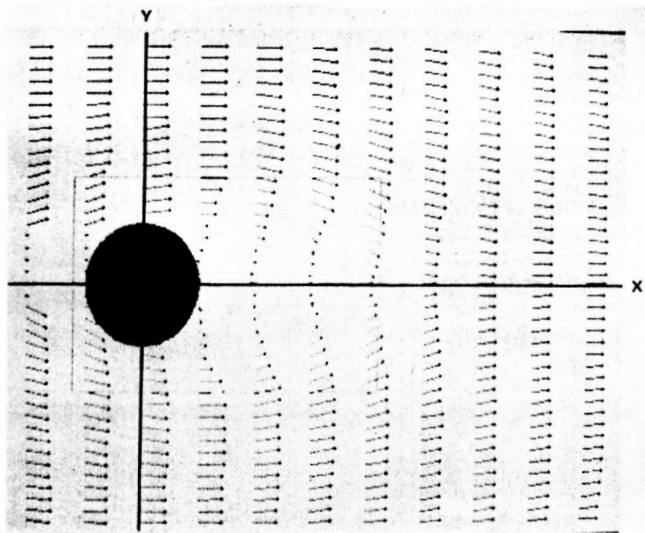


Figure 6. Interpolated velocity field. Velocity vectors are scaled by an arbitrary factor.

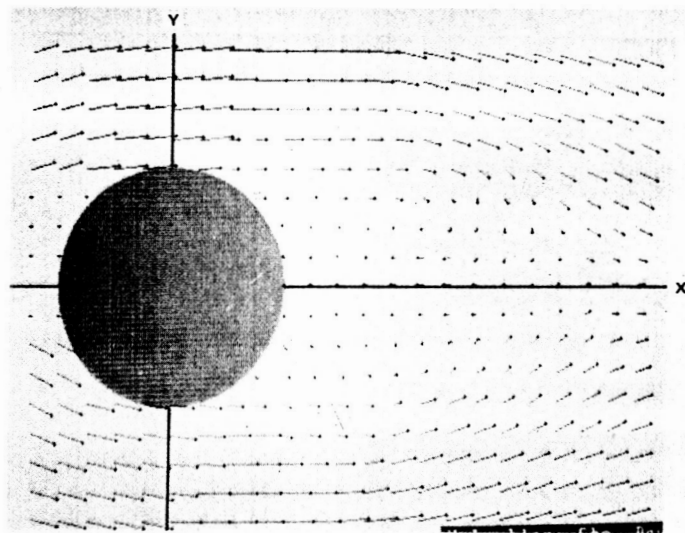


Figure 7. Magnified velocity field in wake. Velocity vectors are scaled by an arbitrary factor.

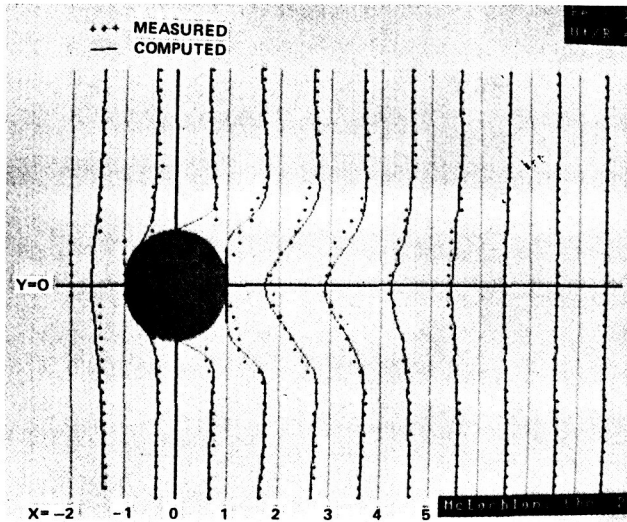


Figure 8. V_x is plotted as a function of y for various values of x . For $x = x_i$, V_x is represented by the horizontal distance from the axis $x = x_i$ to the + mark for the measurement and to the curve for the computation.

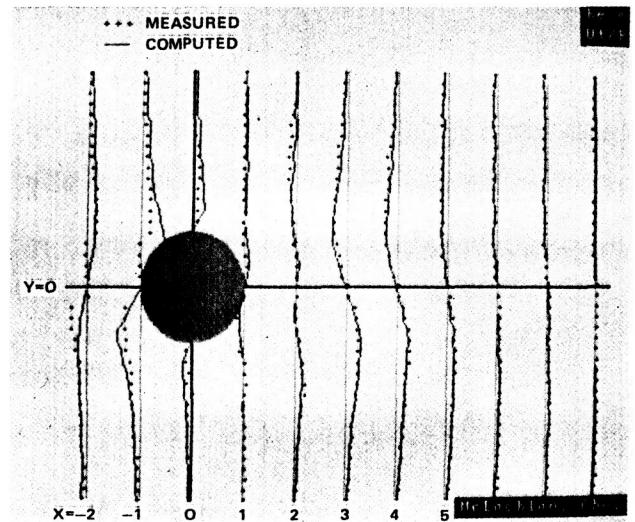


Figure 9. V_y is plotted as a function of y for various values of x . For $x = x_i$, V_y is represented by the horizontal distance from the axis $x = x_i$ to the + mark for the measurement and to the curve for the computation.

In summary, the PC based image processing has been used to determine the velocity field past a circular cylinder with promising results. Efforts will continue to be made to improve image processing techniques applied to measurement of the time dependent velocity field of unsteady flows.

7. ACKNOWLEDGEMENT

The Navier-Stokes computation was made by Dr. S. Davis.

8. REFERENCES

1. R. J. Emrich, Methods of Experimental Physics, Fluid Dynamics, 18, Part A, Academic Press, New York (1981)
2. R. Meynart, "Instantaneous velocity measurements in unsteady gas flow by speckle velocimetry," *Applied Optics*, 22(4), 535-539 (1983)
3. T. D. Dudder and P. G. Simpkins, "Summary of a talk on two-dimensional velocity measurement by laser speckle velocimetry," AIAA Paper No.87-1375 (1987)
4. L. Lourenco and A. Krothapalli, "The role of photographic parameters in laser speckle or particle image displacement velocimetry," *Experiments in Fluids*, 5, 29-32 (1987)
5. J. L. Nayler and R. A. Frazer, "Vortex motion. (i) Preliminary report upon an experimental method of investigating, by aid of kinematograph photography, the history of eddying flow past a model immersed in water," Reports and Memoranda (New Series) No. 332, Tech. Ref. of the Adv. Committee for Aeronautics, 18-25 (1917)
6. M. Schwabe, "Pressure distribution in nonuniform two-dimensional flow," NACA TM 1039 (1935)
7. P. E. Dimotakis, F. D. Debussy and M. M. Koochesfahani, "Particle streak velocity field measurements in a two dimensional mixing layer," *Phys. Fluids*, 24(6), 995 - 999 (1981)
8. K. Imaichi and K. Ohmi, "Numerical processing of flow visualization pictures - measurement of two-dimensional vortex flow," *J. Fluid Mech.*, 129, 283 - 311 (1983)
9. M. Gharib, M. A. Hernan, A. H. Yavrouian and V. Sarohia, "Flow velocity measurement by image processing of optically activated tracers," AIAA Paper No. 85-0172 (1985)
10. J. C. A. Garcia, J. Jimenez, "On the performance of particle tracking," submitted to *J. Fluid Mech.* (1986)



Report Documentation Page

1. Report No. NASA TM-100024	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle Personal Computer (PC) Based Image Processing Applied to Fluid Mechanics		5. Report Date October 1987	
		6. Performing Organization Code	
7. Author(s) Y-C Cho and B. G. McLachlan		8. Performing Organization Report No. A-87329	
		10. Work Unit No. 505-61-01	
9. Performing Organization Name and Address Ames Research Center Moffett Field, CA 94035-5000		11. Contract or Grant No.	
		13. Type of Report and Period Covered Technical Memorandum	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546-0001		14. Sponsoring Agency Code	
15. Supplementary Notes Point of Contact: Y-C Cho, Ames Research Center, M/S 260-1, Moffett Field, CA 94035-5000 (415) 694-4139 or FTS 464-4139 Presented at SPIE 31st International Technical Symposium on Optical and Opto- electronic Applied Science and Engineering, August 16-21, 1987, San Diego, CA			
16. Abstract A PC based image processing system was employed to determine the instantaneous velocity field of a two-dimensional unsteady flow. The flow was visualized using a suspension of seeding particles in water, and a laser sheet for illumination. With a finite time exposure, the particle motion was captured on a photograph as a pattern of streaks. The streak pattern was digitized and processed using various imaging operations, including contrast manipulation, noise cleaning, filtering, statistical differencing, thresholding, etc. Information concerning the velocity was extracted from the enhanced image by measuring the length and orientation of the individual streaks. The fluid velocities deduced from the randomly distributed particle streaks were interpolated to obtain velocities at uniform grid points. For the interpolation we used a simple convolution technique with an adaptive Gaussian window. The results are compared with a numerical prediction by a Navier-Stokes computation.			
17. Key Words (Suggested by Author(s)) Image processing Fluid mechanics Unsteady flow		18. Distribution Statement Unclassified-Unlimited Subject Category - 34	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of pages 8	22. Price A02